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Renewable and Sustainable Energy Reviews 13 (2009) 653–662

RENEWABLE & SUSTAINABLE ENERGY REVIEWS

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Bio-diesel as an alternative fuel for diesel engines—A review

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Received 13 September 2007; accepted 9 October 2007

Abstract

The present review aims to study the prospects and opportunities of introducing vegetable oils and their derivatives as fuel in diesel engines. In our country the ratio of diesel to gasoline fuel is 7:1, depicting a highly skewed situation. Thus, it is necessary to replace fossil diesel fuel by alternative fuels. Vegetable oils present a very promising scenario of functioning as alternative fuels to fossil diesel fuel. The properties of these oils can be compared favorably with the characteristics required for internal combustion engine fuels. Fuel-related properties are reviewed and compared with those of conventional diesel fuel. Peak pressure development, heat release rate analysis, and vibration analysis of the engine are discussed in relation with the use of bio-diesel and conventional diesel fuel. Optimization of alkali-catalyzed transesterification of *Pungamia pinnata* oil for the production of bio-diesel is discussed. Use of bio-diesel in a conventional diesel engine results in substantial reduction in unburned hydrocarbon (UBHC), carbon monoxide (CO), particulate matters (PM) emission and oxide of nitrogen. The suitability of injection timing for diesel engine operation with vegetable oils and its blends, environmental considerations are discussed. Teardown analysis of bio-diesel B20-operated vehicle are also discussed.

Keywords: Bio-diesel; Alternative fuels; Internal combustion engine fuels; Transesterification; Performance and emission of bio-diesel blends

Contents

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2007.10.007

1. Introduction

Fast depletion of fossil fuels is demanding an urgent need to carry out research work to find out the viable alternative fuels. Diesel fuel is largely consumed by the transportation sector. Thermodynamic tests based on the engine performance evaluations have established the feasibility of using vegetable oils. It has been found that vegetable oils hold special promise in this regard, because they can be produced from the plants grown in rural areas. Vegetable oils from crops such as soyabean, peanut, sunflower, rape, coconut, karanja, neem, cotton, mustard, jatropha, linseed and coster have been evaluated in many parts of the world in comparison with other non-edible oils. Karanja (pungamia) is an oil seed-bearing tree, which is non-edible and does not find any suitable application with only 6% being utilized of 200 million tonnes per annum [1].

1.1. Indian scenario

At present, India is producing only 30% of the total petroleum fuels required. The remaining 70% is being imported, which costs about Rs. 80,000 crore every year. It is an astonishing fact that mixing of 5% bio-diesel fuel to the present diesel fuel is made available in our country, which can save about Rs. 4000 crore every year. It is estimated that India will be able to produce 288 metric tonnes of bio-diesel by the end of 2012, which will supplement 41.14% of the total demand of diesel fuel consumption in India. The planning commission of India has launched a bio-fuel project in 200 districts from 18 states in India. It has recommended two plant species, viz. jatropha (*Jatropha curcas*) and karanja (*Pungamia pinnata*) for bio-diesel production [2–17]. The recent auto fuel policy document states that bio-fuels are efficient, eco-friendly and 100% natural energy alternative to petroleum fuels [18].

1.2. International scenario

Use of bio-diesel is catching up all over the world especially in developed countries. In Malaysia, the tropical climate encourages production of bio-diesel from palm oil [1]. The US is contributing 25% of the world green house gases: i.e., oil and coal. We also need to reorganize its 70% of oil consumption is in transportation. The cost of bio-diesel is $3.00 a gallon (~4.5 l). With the tax subsidy available in the law now, it could be sold for about $1.80. It is clearly known that the future depends on bio-fuels as replacement for fossil fuels.

At present, USA uses 50 million gallons and European countries use 350 million gallons of bio-diesel annually. It is mixed with 20% of bio-diesel in fossil diesel. France is the country which uses 50% of bio-diesel mixed with diesel fuel. In Zimbabwe, 4 million jatropha has been planted in 2000 ha by the end of 1997. In Nicaragua, one million *Jatropha curcas* has been planted in 1000 ha. The harvest of pods reached 3,33,000 tonnes in the 5th year with a seed of 5000 tonnes and the oil extracted was approximately 1600 tonnes per annum. In Nepal, 22.5 ha of area are planted with 40,000 rooted cuttings of *Jatropha curcas*. The rural women co-operative have been trained to extract oil, produce soap and use 30:70 mix [oil/kerosene] of oil and kerosene in stove without smoke [2,9,19].

2. Historical background

Bio-diesel production is not something new, because the concept of using vegetable oil as fuel dates back to 1895. Rudolf Diesel developed the first diesel engine which was run with vegetable oil in 1900. The first engine was run using groundnut oil as fuel [2]. In 1911, Rudolf Diesel stated that the diesel engine can be fed with vegetable oil and would help considerably in the agricultural development of the countries which use it. In 1912, Rudolf Diesel said, “The use of vegetable oils for engine fuels may seem insignificant today. But such oils may become in course of time as important as petroleum and the coal tar products of the present time” [20]. After eight decades, the awareness about environment rose among the people to search for an alternative fuel that could burn with less pollution. Rudolf Diesel’s prediction is becoming true today with more and more bio-diesel being used all over the world.

3. Vegetable oil and its blends

The unprocessed oil can also be used in diesel engines, but with required adjustment to the engine-driving habits. Unlike diesel fuel, vegetable oil consists mostly of saturated hydrocarbons and those vegetable oils are triglycerides, consisting of glycerol esters of fatty acids [20]. Vegetable oils have a different chemical structure. Up to three fatty acids are

Table 1
Chemical structure of common fatty acids

Name of fatty acid	Chemical name of fatty acids	Structure (*xx*:*y*)	Chemical formula
Lauric	Dodecanoic	12:0	$C_{12}H_{24}O_2$
Myristic	Tetradecanoic	14:0	$C_{14}H_{28}O_2$
Palmitic	Hexadecanoic	16:0	$C_{16}H_{32}O_2$
Stearic	Octadecanoic	18:0	$C_{18}H_{36}O_2$
Arachidic	Eicosanoic	20:0	$C_{20}H_{40}O_2$
Behenic	Docosanoic	22:0	$C_{22}H_{44}O_2$
Lignoceric	Tetracosanoic	24:0	$C_{24}H_{48}O_2$
Oleic	*cis*-9-Octadecenoic	18:1	$C_{18}H_{34}O_2$
Linoleic	*cis*-9,*cis*-12-Octadecadienoic	18:2	$C_{18}H_{32}O_2$
Linolenic	*cis*-9,*cis*-12,*cis*-15-Octadecatrienic	18.3	$C_{18}H_{30}O_2$
Erucle	*cis*-13-Docosenoic	22:1	$C_{32}H_{42}O_2$

xx indicates the number of carbons and *y* the number of double bonds in the fatty acid chain.

linked to a glycerin molecule with ester linkages. The fatty acids vary in their carbon chain length and in number of double bonds. Some of the fatty acids commonly found in vegetable oil [21] are listed in Table 1.

Palmitic (16:0) and stearic (18:0) are the two most common saturated fatty acids with every vegetable oil containing at least a small amount of each one [20].

3.1. Properties of vegetable oil

The fuel properties of vegetable oil as listed in Table 2 indicates that the kinematic viscosity of vegetable oil varies in the range of 30–40 cSt at 38 °C. The high viscosity of these oils is because of their large molecular mass in the range of 600–900. This is about 20 times higher than that of diesel fuel. The flash point of vegetable oil is very high (above 200 °C). The heating values are in the range of 39–40 MJ/kg when compared to diesel fuel (about 45 MJ/kg). The presence of chemically bound oxygen in vegetable oil lowers their heating values by about 10%. The cetane numbers are in the range of 32–40 [21].

Blending of vegetable oils with diesel fuel would solve the problems of diesel engine operation with neat vegetable oil. Diesel fuel dissolves quite well with vegetable oils. The vegetable oils have their own advantages as they are available everywhere in the world. They are renewable like the vegetables, which produce oil seeds that can be planted year after year. They are "greener" to the environment as they seldom contain sulphur element in them. This makes vegetable fuel studies become current among the various popular investigations. Attempts have been made, and the test results have proved that vegetable oils are feasible substitutes for diesel fuel. But there is still a lot of work that has to be done to make vegetable oil really applicable to diesel engines instead of the ordinary diesel fuel [22].

Vellguth [23], Schramm et al. [24], reported that vegetable oils can power diesel engine, but unmodified direct injection cokes up. The engines when operated on these fuels for any length of time with precombustion in a swirl chamber engines. The performance of the engine with vegetable oils as fuel is better.

Senthilkumar et al. [25] reported that the injection timing for diesel is 27° BTDC and injection timing for vegetable oil and esters of vegetable oil is 29° BTDC for better performance, for a Kirloskar AV1 four stroke, water-cooled single cylinder engine.

Table 2
Properties of vegetable oil

Vegetable oil	Kinematic viscosity at 38 °C (mm^2/S)	Cetane no.	Heating value (MJ/kg)	Cloud point (°C)	Pour point (°C)	Flash point (°C)	Density (kg/l)
Corn	34.9	37.6	39.5	−1.1	−40.0	277	0.9095
Cottonseed	33.5	41.8	39.5	1.7	−15.0	234	0.9148
Crambe	53.6	44.6	40.5	10.0	−12.2	274	0.9048
Linseed	27.2	34.6	39.3	1.7	−15.0	241	0.9236
Peanut	39.6	41.8	39.8	12.8	−6.7	271	0.9026
Rapeseed	37.0	37.6	39.7	−3.9	−31.7	246	0.9115
Safflower	31.3	41.3	39.5	18.3	−6.7	260	0.9144
Sesame	35.5	40.2	39.3	−3.9	−9.4	260	0.9133
Soya bean	32.6	37.9	39.6	−3.9	−12.2	254	0.9138
Sunflower	33.9	37.1	39.6	7.2	−15.0	274	0.9161
Palm	39.6	42.0	–	31.0	–	267	0.9180
Babassu	30.3	38.0	–	20.0	–	150	0.9460
Diesel	3.06	50	43.8	–	−16	76	0.855

3.2. Suitability

The following unique properties of vegetable oils help us to replace the diesel fuel:

- Cetane number (refer Table 1) is similar or close to that of diesel fuel.
- Heating values of various vegetable oils are nearly 90% to those of diesel fuel.
- Long chain saturated, unbranched hydrocarbons are especially suitable for conventional diesel fuel. The long, unbranched hydrocarbon chains in the fatty acids meet this requirement.
- The normal chain length for plant oils is from 12 to 22 carbon atoms, with 0 to 3 double bonds that are responsible for the physico-chemical properties of the oil.

3.3. Problems in using vegetable oils in CI engines

It has been found that [21,26] neat vegetable oil can be used as diesel fuel in conventional diesel engines, which leads to the following problems:

1. Types and grade of oil and local climatic conditions.
2. The injection, atomization and combustion characteristics of vegetable oils in diesel engine are significantly different from those of the diesel fuel.
3. High viscosity of vegetable oil interferes with the injection process and leads to poor fuel atomization.
4. The inefficient mixing of oil with air contributes to incomplete combustion, leading to heavy smoke emission.
5. The high flash point attributes to lower volatility characteristics.
6. Both cloud and pour points (refer Table 2) are significantly higher than that of diesel fuel. These high values may cause problems during cold weather.
7. Lube oil dilution.
8. High carbon deposits.
9. Ring sticking.
10. Scuffing of the engine liner.
11. Injection nozzle failure.

These problems can be solved, if the vegetable oils are chemically modified to bio-diesel, which is similar in characteristics to diesel fuel [20,26].

3.3.1. Performance characteristics of net vegetable oil

Barsin and Humke [27] reported that when diesel engine was run with vegetable oil as fuel, produced equivalent power to that of the diesel fuel because fuel mass flow energy delivery increased due to higher density and viscosity of vegetable oil. It also increased fuel flow by reducing internal pump leakage. The lower mass-based heating values of vegetable oils required larger mass fuel flow to maintain constant energy input to the engine.

3.3.2. Emission characteristics of net vegetable oil

Carbon monoxide (CO) emission was increased in light and medium loads and decreased in higher load. Particulate matter emissions were reduced in light and medium loads but it increased in higher load.

3.4. Vegetable oil blends

Wang et al. [22] reported that the major disadvantage of vegetable oils is their inherent high viscosity. Modern diesel engines have fuel injection system that is sensitive to viscosity change. High viscosity may lead to poor atomization of the fuel, incomplete combustion, choking of the injectors, ring carbonization and accumulation of the fuel in the lubricating oils. A way to avoid those problems and to improve the performance is to reduce the viscosity of vegetable oil. There are some methods to reduce the viscosity of vegetable oil such as fuel blending. It has the advantages of improving the use of vegetable oil as fuel with minimum processing and engine modification.

3.4.1. Performance of vegetable oil blends

The blends of 25% vegetable oil with 75% diesel fuel, 50% vegetable oil with 50% diesel fuel, 75% vegetable oil with 25% diesel fuel and 100% vegetable oil as diesel fuel were used to conduct the test on a Lister–Petter TS2 model, twin cylinder air cooled diesel engine. The various fuel properties of diesel and blend with vegetable oil are given in Table 3.

The diesel fuel has the highest gross calorific value and lowest viscosity, when compared with various blends. It was found that the higher percentages of vegetable oil in the blends increases the viscosity and lowers the gross calorific value. The pure vegetable oil has lowest gross calorific value and highest viscosity.

The Fig. 1 shows the variation of exhaust gas temperature with percentage of load for different fuels. The exhaust gas temperature rise with the increase of engine load for all the fuels. It was observed that the exhaust gas temperature at different load when using different fuels are nearly the same. Only in the case of 25% of diesel fuel with 75% of vegetable oil the exhaust temperature is slightly higher than the other fuels.

Fig. 2 shows the variation of BSFC with percentage of load for different fuels. The differences of BSFCs are very small at different engine load, when using different fuels.

3.4.2. Emissions of vegetable oil and its blends

Fig. 3 shows the variation of the CO emission with percentage of load for different fuels. The CO emission for the

Table 3
Fuel properties

Fuel	Gross calorific value (MJ/kg)	Viscosity (poise)	Relative density
A	45.357	0.0445	0.850
B	43.288	0.087	0.877
C	42.158	0.162	0.890
D	40.841	0.368	0.907
E	39.358	0.669	0.927

A, 100% diesel; B, 25% vegetable oil + 75% diesel; C, 50% vegetable oil + 50% diesel; D, 75% vegetable oil + 25% diesel; E, 100% vegetable oil.

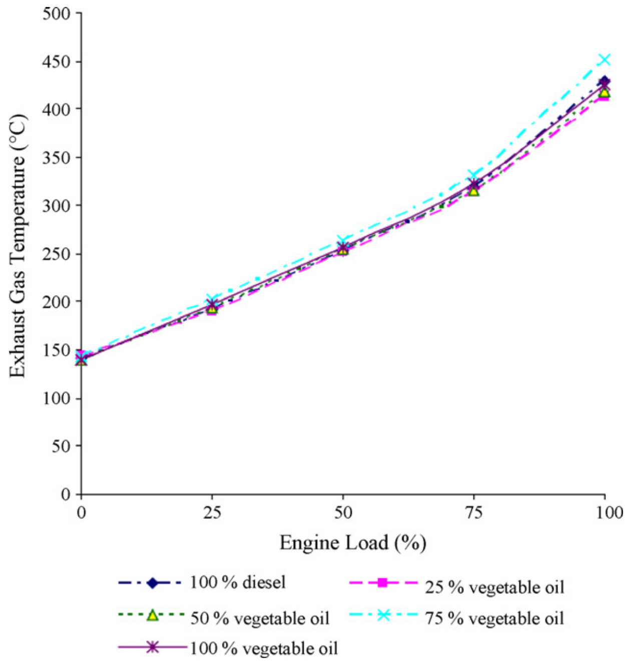

Fig. 1. Variation of exhaust gas temperature of different fuels.

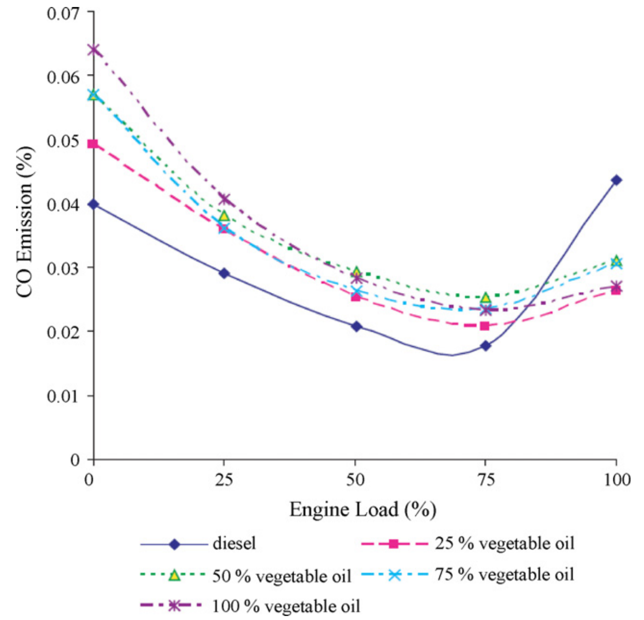

Fig. 3. Variation of CO emission with percentage of load for different fuels.

vegetable oil and the blends are lower than that of diesel fuels at the full load, whereas the CO emissions are all slightly higher for lower loads.

Fig. 4 shows the variation of CO_2 emissions with percentage of load for different fuels. It is observed that all the CO_2 emission of diesel fuels is higher than that of the blended fuels. This may be because the vegetable oil contains oxygen elements the common context is relatively lower in the same volume of fuel consumed at the same engine load, consequently, the CO_2 emissions from the vegetable oil and its blends are lower.

Fig. 5 shows the variation of HC emission with percentage of load for different fuels, it is observed that HC emission of the various blends was lower in partial load, but increased at higher engine load. These results are in accordance with Senthilkumar et al. [25]. This is due to the availability of relatively less oxygen for the reaction when more fuel is injected into the engine cylinder at higher engine load.

Fig. 6 shows the variation of NO_x emission with percentage of load for different fuels. It is observed that NO_x emission from the vegetable oil and the vegetable oil/diesel fuel blends are lower than those of diesel fuel. The reduction of the NO_x emission is possibly due to the lower calorific value of vegetable oil and its blends. This is the most important emission characteristics of vegetable oil. Ziejewski and Goettler [28] reported that the unregulated emission PAH was lower in the

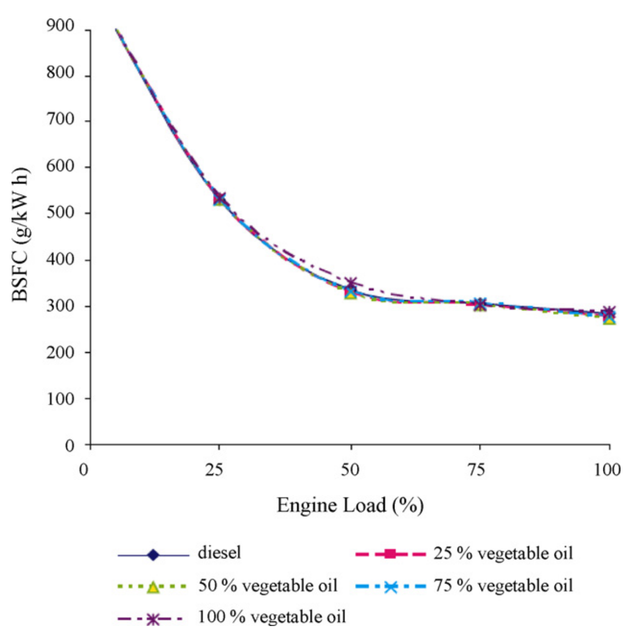

Fig. 2. Variation of brake-specific fuel consumption of different fuels.

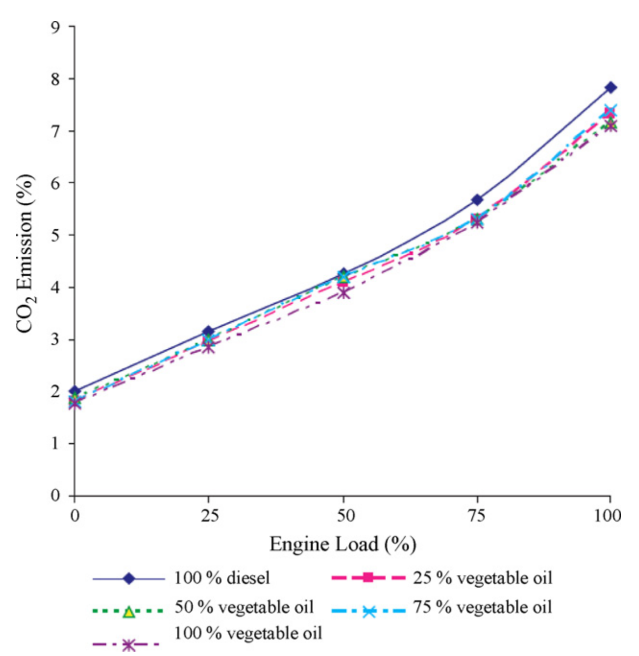

Fig. 4. Variation of CO_2 emission with percentage of load for different fuels.

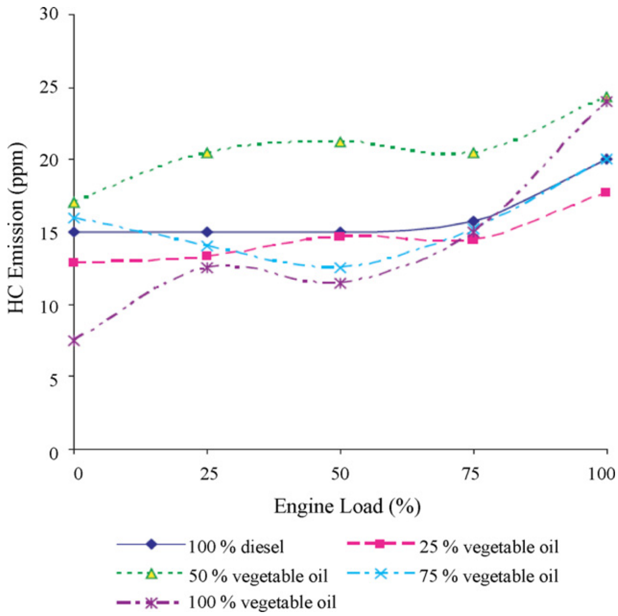

Fig. 5. Variation of HC emissions of different fuels.

blends of sunflower with diesel blend up to 5–95% using gas chromatograph.

4. Bio-diesel standards

In the United States, an ASTM standard was suggested for neat bio-diesel specification. Table 4 summarizes the bio-diesel B100 specification last updated on June 2006 [29].

4.1. Advantages of bio-diesel

- Bio-diesel is non-toxic.
- Bio-diesel degrades four times faster than diesel.
- Pure bio-diesel degrades 85–88% in water.
- Blending of bio-diesel with diesel fuel increases engine efficiency.
- The higher flash point makes the storage safer.
- Bio-diesel is an oxygenated fuel, thus implying that its oxygen content plays a role in making fatty compounds suitable as diesel fuel by ''cleaner'' burning.
- 90% reduction in cancer risks, according to Ames mutagenicity tests.
- Provides a domestic, renewable energy supply.
- Bio-diesel does not produce greenhouse effects, because the balance between the amount of CO_2 emissions and the amount of CO_2 absorbed by the plants producing vegetable oil is equal.
- Bio-diesel can be used directly in compression ignition engines with no substantial modifications of the engine.
- Bio-diesel contains no sulphur and is generally suitable to match the future European regulations which limit the sulphur content to 0.2% in weight in 1994 and 0.05% in 1996.
- Chemical characteristics revealed lower levels of some toxic and reactive hydrocarbon species when bio-diesel fuels were used.
- The emissions of PAH and nitro PAH compounds were substantially lower with bio-diesel are compared to conventional diesel fuel.
- The larger reductions in PAH are not unexpected when considering the bio-diesel contains no aromatics and no PAH compounds [7,30–33].

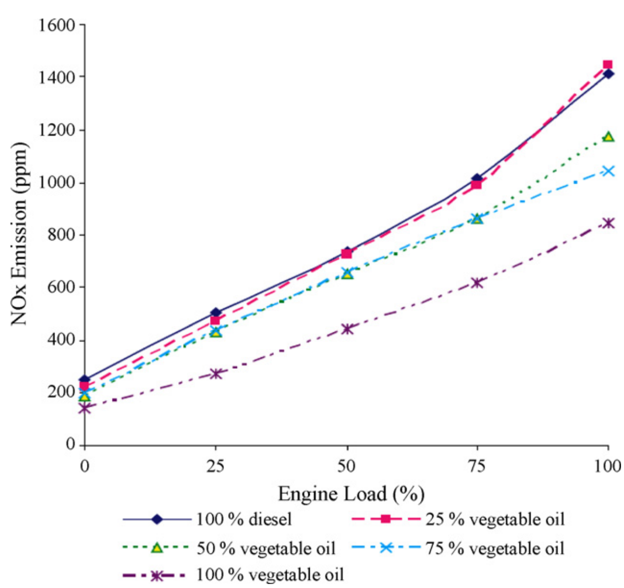

Fig. 6. Variation of NO_x emission of different fuels.

4.2. Disadvantages of bio-diesel

- Slight decrease in fuel economy on energy basics (about 10% for pure bio-diesel).
- Density is more than diesel fuel in cold weather, but may need to use blends in sub-freezing conditions.
- More expensive due to less production of vegetable oil [30].

4.3. Production of bio-diesel

In general, vegetable oil contains 97% of triglycerides and 3% di- and monoglycerides and fatty acids. The process of removal of all glycerol and the fatty acids from the vegetable oil in the presence of a catalyst is called transesterification. The vegetable oil reacts with methanol and forms esterified vegetable oil in the presence of sodium/potassium hydroxide as catalyst. The transesterification represented in Eq. (1) [20,21,26,30,34–37].

Transesterification process:

$$
\begin{array}{l}
\mathrm{H} \\
| \\
\mathrm{H-C-OOR} \\
| \\
\mathrm{H-C-OOR' + 3CH_3OH} \\
| \\
\mathrm{H-C-OOR''} \\
| \\
\mathrm{H} \\
\text{Vegetable oil}
\end{array}
\quad
\underset{\text{Solvent}}{\overset{\text{Catalyst}}{\rightleftarrows}}
\quad
\begin{array}{ll}
\mathrm{H} & \\
| & \\
\mathrm{H-C-OH} & \mathrm{CH_3OOR} \\
| & \\
\mathrm{H-C-OH} & \mathrm{+\ CH_3OOR'} \\
| & \\
\mathrm{H-C-OH} & \mathrm{CH_3OOR''} \\
| & \\
\mathrm{H} & \\
\text{Glycerol} & \text{Methyl ester}
\end{array}
\tag{1}
$$

Table 4
Bio-diesel, B100, specification-ASTM D6751-06

Property	ASTM Method	Limits	Units
Flash point	D93	130 min.	°C
Water and sediment	D2709	0.050 max.	vol.%
Kinematic viscosity, 40 °C	D445	1.9–6.0	mm^2/s
Sulfated ash	D874	0.020 max.	mass%
Sulfur	D5453	–	–
S 15 grade	–	15max.	ppm
S 500 grade	–	500 max.	–
Copper strip corrosion	D130	No.3 max.	–
Cetane	D613	47 min.	–
Cloud point	D2500	Report	°C
Carbon residue 100% sample	D4530[a]	0.050 max.	mass%
Acid number	D664	0.50 max.	mg KOH/gm
Free glycerin	D6584	0.020 max.	mass%
Total glycerin	D6584	0.240 max.	mass%
Phosphorus content	D4951	0.001 max.	mass%
Distillation temperature, atmospheric equivalent temperature, 90% recovered	D1160	360 max.	°C
Sodium/potassium	UOP391	5 max. combined	ppm

[a] The carbon residue shall be run on the 100% sample.

4.3.1. Chemistry of transesterifaction process

The overall transesterifaction reaction is given by Eq. (1). However, consecutive and reversible reactions are believed to occur. These reactions are represented in Eq. (2).

Chemistry of transesterification process:

$$\begin{aligned} &\text{Triglycerides} + \text{ROH} \rightleftarrows \text{diglycerides} + \text{R}^1\text{COOR},\\ &\quad \text{diglycerides} + \text{ROH} \rightleftarrows \text{monoglycerides} + \text{R}^2\text{COOR},\\ &\quad \text{monoglycerides} + \text{ROH} \rightleftarrows \text{glycerol} + \text{R}^3\text{COOR} \end{aligned} \tag{2}$$

The first step is the conversion of triglycerides to diglycerides followed by the conversion of diglycerides to monoglycerides and of monoglycerides to glycerol yielding one methyl ester molecule from each glycerides at each step [38,39]. Meher et al. [1] reported that the experimental study revealed that the optimum reaction conditions for methanolysis of karanja oil was 1% KOH as catalyst. MeOH/oil of molar ratio 6:1, reaction temperature 65 °C, at the rate of mixing 360 rpm for a period of 3 h. The yield of methyl ester was >85% in 15 min and reaction was almost complete in 2 h with an yield of 97–98% with 12:1 molar ratio of MeOH oil or higher, the reaction was completed within 1 h. The reaction was incomplete with a low rate of stirring, i.e. 180 rpm; whereas, stirring at high rpm was a time-efficient process.

4.4. Bio-diesel and its blends

Properties of pungam methyl ester [40]: the fuel properties of karanja oil, karanja methyl ester and its blends are tabulated in Table 5.

4.5. Performance of bio-diesel blends

Raheman and Phadatare [40] reported that the torque produced for B20 and B40 were 0.1–1.3% higher than that of diesel due to complete combustion of fuel. In case of B60–B100, it was reduced by 4–23% when compared with diesel fuel for single cylinder, four stroke, direct injection, water-cooled engine produced 7.5 kW power at 3000 rpm.

The brake-specific fuel consumption for B20 and B40 was 0.8–7.4% lower than diesel. In the case of B60–B100 the brake-specific fuel consumption was 11–48% higher than diesel because of a decrease in the calorific value of fuel with an increase in bio-diesel percentage in the blends. The brake thermal efficiency was 26.79 and 29.19% for B20 and B40, respectively, which was higher than that of diesel (24.64%).

The maximum brake thermal efficiency obtained from B60, B80 and B100 was 24.26, 23.96, and 22.71%, respectively. This is due to the reduction in calorific value and increase in fuel consumption compared to B20. These results are in accordance

Table 5
Fuel properties of karanja oil, karanja methyl ester and its blends

Sl. no.	Fuel	Relative density	Kinematic viscosity (mm^2/S)	Calorific value (MJ/kg)	Flash point (°C)
1	Karanja oil	0.912	27.84	34.00	205
2	B100	0.876	9.60	36.12	187
3	B20	0.848	3.39	38.28	79
4	B40	0.856	4.63	37.85	81
5	B60	0.864	5.42	37.25	84
6	B80	0.869	6.56	36.47	92
7	Diesel	0.846	2.60	42.21	52

B100, 100% bio-diesel; B20, 20% bio-diesel + 80% diesel; B40, 40% bio-diesel + 60% diesel; B60, 60% bio-diesel + 40% diesel; B80, 80% bio-diesel + 20% diesel.

with [25,26,41]. Kadiyala et al. [41] reported that the peak cylinder pressure and rate of pressure rise with the use of pungam methyl ester and diesel fuel varied with marginal difference. The heat release rate curves, diffused combustion in the case of pungam methyl ester at full load running of the engine are comparatively better than diesel fuel.

The average spectrum values with the diesel fuel operation are more because of the higher power development. The FFT analyzer frequency range of 1–2000 Hz was used to monitor the engine vibration for both diesel and methyl ester of pungamia oil. Change in the vibrational phase recorded on the cylinder indicates lagging leading of the burning properties of the oils in comparison. This was synonymous with the net heat graphs indicating early heat release with the pungam methyl ester at higher load.

4.5.1. Emission of bio-diesel blends

Many researchers like Barnwal et al. [21], Vellguth [23], Senthilkumar et al. [25], Sundarpandian and Devaradjane [26], Palanisamy and Manoharan [30], Banapurmath et al. [31], Rahema and Phadatare [40], and Shankar et al. [42] reported that the CO, CO_2 and UBHC emissions are reduced in bio-diesel and its blends, because bio-diesel is oxygen in structure and it burns clearly all the fuels. Senthilkumar et al. [25], Shankar et al. [42] reported that NO_x emissions are slightly increased in bio-diesel and its blends. This is due to the higher temperature in the combustion chamber using bio-diesel.

Senthilkumar et al. [25] reported that to reduce the NO_x emission by operating engine in dual fuel mode i.e., fuel with high octane number as primary fuel and high cetane number as pilot fuel. Vegetable oil and bio-diesels are high cetane number (40–45) is injected through a standard injection system. The primary fuel is orange oil which has high octane number (143) is admitted along with the in take air stream. It reducing the smoke and NO_x emission, and increases the HC and CO emissions. Greeves and Wang Lucas [43] and Nurannabai et al. [44] reported that exhaust gas recirculation can be used to give NO_x reduction up to 50% and reduce smoke emission by 15% by EGR.

4.5.2. Environmental considerations

In view of environmental considerations, bio-diesel is considered Carbon neutral because all the CO_2 released during consumption had been sequestered from the atmosphere for the growth of vegetable oil crops. The combustion of bio-diesel has reported to emit lesser pollutants compared to diesel. This indicates that the engine exhaust contains no SO_2, and shows decreasing emissions of PAH, CO, HC, soot and aromatics. The NO_x emission is reported to be in the range between $\pm 10\%$ as compared to diesel depending on engines combustion characteristics.

4.6. Teardown analysis

Fraer et al. [45] reported that 1996, Mack MR 688 p model vehicle with six cylinders its compression ratio of 16.5:1, producing the power 300 hp at 1950 rpm used in postal purposes. The engine and fuel system components were disassembled, inspected and evaluated to compare wear characteristics after 4 years of operation and more than 6,00,000 miles accumulation on B20, no difference in wear or other issues were noted during the engine teardown. The cylinder heads of B20 engines contained a heavy amount of sludge around the rocker assemblies that was not found in the diesel engines. The sludge contained high levels of sodium possibly caused by accumulation of soaps in the engine oil. The B20 engines required injector nozzle replacement over the evaluation and teardown period this is due to out of specification of fuel. The biological contaminants may be the cause of filter plugging.

5. Recommendation for the development of bio-fuels [46]

As the stock of fossil fuel is getting depleted, emphasis should be given to renewable sources of fuel such as bio-fuel crops and tree-borne oilseeds:

- DST funding is required for land resources management, water resources, mineral and fossil fuels.
- Design, develop and popularize appliances and equipments specifically for rural application.
- Prima facie, bio-diesel seems to have significant potential to contribute to India's energy security, the need of the hour is to undertake R&D on sustainable plantation management, oil extraction and use environmental and social impact assessment and build institutional models.
- To develop fuel wood and bio-diesel plantation to reduce drudery in collecting fuel wood for meeting house-hold energy equipment.
- A common platform for interaction with farmers extension personnel, researchers and technologists with media personnel must be created.
- Contact training programs to sensitize media personnel on latest technologies and developments related to rural development.
- Creating awareness regarding loan, insurance facilities subsidies, etc.

5.1. Need for a policy initiative [47]

- Initiate dialogue on classification of non-edible vegetable oils based on their origin and practices, from that of natural forest/ social forestry/avenue plantations.
- Cultivated vegetable oils can be dedicated/diverted to agricultural operations to source energy requirements.
- Tree-borne oils of forest origin can go for central pool for blending as a transportation fuel.
- Need for a long-term national policy on utilization of these oils as per their allocations.
- Sustain this concept till it is socially reproduced, and becomes an agricultural activity by the farmers.
- Energy recovery from deoiled cakes, be encouraged as an on-farm activity, for fertilizer, and for dual fuel mode engine applications.

- Arriving at a benchmark on the engine capacity, subsidize the interest rates, as an incentive.

5.2. Translation of the policy initiative [47]

- Establish a separate permanent board/Directorate of bio-fuels strictly for agricultural operations.
- The districtwise agricultural energy requirements be translated, into the extent of crop to be grown.
- Ensure for every 200 ha+ of such crop (e.g., jatropha), at least two processing plants be encouraged.
- In a time frame, to develop and make available the engines to run on SVO/bio-diesel, based on need and convenience.
- Additional incentive for dual fuel mode of operation to save vegetable oil for other applications.
- Invite involvement of local engineering institutions to verify the quality aspects of the fuel by providing infrastructure, to act as a resource centers.
- Necessary training and extension programs be motivated with these centers.
- Ensure rural entrepreneurial/work opportunities, by encouraging small-scale industrial activity.
- Put the mechanism in place to deliver energy products available locally, to all the stakeholders.
- Transition to bio-fuels can be developed based on cropping pattern/site and size-specific operations, by measuring the actual energy saved.
- For this exercise state bio-fuel boards can engage charted engineering/qualified personnel to make such evaluation once in 3 months.
- Savings on fossil fuels, be rewarded, as an incentive to the bio-fuel boards of the respective EBs/states.
- The CDM cash credits/rewards can be distributed, among the stakeholders as a support price for the raw material/to the distribution mechanism.

5.3. Bio-diesel policy [18]

Beginning 1 January 2006, the public sector OMCs (oil marketing companies) will be purchasing bio-diesel (B100) at Rs. 25 a liter for blending with diesel (HSD) to the extent of 20% in phases. Unveiling the new bio-diesel purchase policy on 13 October, the former minister for petroleum and natural gas, Mr. Mani Shankar Aiyar, said that to start with, 5% of bio-diesel, a non-edible oil extracted from jatropha and pungamia, would be mixed with diesel during trial runs. At a later stage, in phases, the B100 blending with diesel is to be increased to 20%. Mr. Aiyar noted that automobile engines would not require any modification for using diesel doped with 20% bio-diesel as fuel. Only those bio-diesel manufacturers who get their samples approved and certified by the oil companies, and get registered as authorized suppliers will be eligible for assured purchase of product, the new policy statement said. Accordingly starting 1 January 2006, the OMCs–IOC, BPCL, and HPCL would purchase through select purchase centers, bio-diesel that meets the fuel quality standards prescribed by the bureau of industrial standards.

6. Summary and conclusion

- Methyl ester of bio-diesel (B100) can be directly used in diesel engines without any modifications for short term with slightly interior performance than that of diesel.
- Brake thermal efficiency for bio-diesel is slightly increased in B20.
- Brake-specific energy consumption for B20 is reduced slightly.
- The CO, CO_2, HC PAH emissions are reduced.
- NO_x emissions are slightly increased it should be reduced by EGR or dual fuel mode.
- A blend of 20% by volume of bio-diesel fuel in diesel does not affect any of the measured performance or emission characteristics.
- Addition of small quantities of bio-diesel to mineral diesel is a suitable strategy for increasing alternative fuel consumption, atleast in agricultural engines.
- The B20 is best alternative fuel for diesel.

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